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AN ANALOG SYSTEM FOR REDUCING ABLATION TEST DATA

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NOTICE

AN ANALOG SYSTEM FOR REDUCING ABLATION TEST DATA

P[redacted]
David M. Caum

ABSTRACT: An analog data reduction system was devised to reduce strip chart records of the internal temperature of an ablating body to convenient graphs of effective thermal diffusivity (α^*) vs. temperature. The system is a necessary adjunct to the NOL alpha-rod technique used for experimentation with ablation materials. The analog system reduces computation time and increases precision compared with manual methods and is more convenient, when using strip chart records, than digital techniques. In addition, the overall precision of the experiment does not require the accuracy of a digital computer.

A schematic, a block diagram, and typical graphs comparing analog data with data obtained using a 5-point parabolic fit are presented. Minimum analog error is about 3% when simple known functions are used as inputs. Using irregular test records as inputs results in a higher error of 5 to 10%.

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NOLTR 65-3 17 March 1965

AN ANALOG SYSTEM FOR REDUCING ABLATION TEST DATA

This report describes the development of an analog system that was designed to increase the accuracy and speed of reducing ablation data from the NOL "Alpha-Rod" Test. This improvement in data handling aids in the analysis of high temperature materials behavior and in supplying information for programs now in progress. The work was done under the High Temperature Materials Program, WepTask RMMP-23 054/212-1/F009-06-003.

R. E. ODENING
Captain, USN
Commander

ALBERT LIGHTBODY
By direction

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ILLUSTRATIONS

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INTRODUCTION

Over the past several years, the NOL "alpha-rod" test has been a useful tool for measuring the ablative performance of materials in high thermal environments. A serious drawback, however, was that manual reduction of the data was time consuming, inaccurate and tedious.

To eliminate this problem, an analog system of data reduction was developed. With this apparatus, computation times were reduced from 2-3 hours per test to 5-10 minutes. In addition, the accuracy was increased to an acceptable level. The average error with typical data input falls in a range of 5 to 10% while the minimum is about ±3%.

The remainder of this report describes the general features of the analog system, the advantages of using such a system, and the accuracy obtained. Details of the system and its method of operation are included in the appendices.

This report was written primarily to familiarize the uninitiated with the general features and operation of the analog system. It may also be useful to those who are planning similar systems.

THE "ALPHA-ROD" TEST

GENERAL

The NOL "alpha-rod" test is designed to obtain the recession rate and effective thermal diffusivity, α^*, of a material in a dynamic situation, undergoing steady-state ablation with unidirectional heat conduction (refs. (a),(b) and (c)). The outputs of the test are: a temperature-time record from a thermocouple imbedded in a rod shaped specimen, and a record of the recession of the front face vs. time from a potentiometer coupled to the specimen through an automatic servo-positioning system.

EFFECTIVE THERMAL DIFFUSIVITY

The effective thermal diffusivity is found by solving the equation:

$$\alpha^* = (T - T_o)U^2/{}^{dT}/_{dt}$$

where:

α^* = the effective thermal diffusivity (which includes latent and chemical heat effects as well as the usual specific heat)

T = temperature at some point a, inside the specimen

dT/dt = slope of the temperature-time record at point a

T_o = the initial temperature of the specimen

U = the steady-state ablation rate.

The derivation of the above equation is found in references (b) and (c), along with a more complete description of the "alpha-rod" test.

SOLUTION FOR α^*

Some possible techniques for the solution of the alpha equation are:

1. Manual calculations using tangents obtained by manual alignment techniques.

2. Manual calculations using tangents obtained by a 5-point parabolic fit, curve smoothing technique, reference (d).

3. Digital data reduction using tangents obtained from incremental points (as found by cross-hairs on an automated plotting board) or using single points to obtain a 5-point parabolic fit from which a derivative is found.

4. Analog data reduction.

The major factor influencing the accuracy of all four methods of calculating α^* is the slope measurement, dT/dt. In Figure 1, a typical temperature-time record, at temperatures approaching the initial, ambient temperature T_O, the slope tends to be small. Thus, slight changes of temperature in this region cause larger changes in the slope of the curve; which in turn causes large fluctuations in α^*. In the higher temperature regions the slope is greater and is increasing at a faster rate; in this region small fluctions in temperature have little effect on α^*.

MANUAL CALCULATIONS

The main drawback in hand calculating α^* is accurate measurement of the slope of the temperature-time record. There are several procedures for estimating a tangent to an irregular curve, but in every case their accuracy depends on the exactness of the tangent line and the precision to which the slope is measured. In addition, a large number of measurements are needed to get a smooth trace of α^* vs. temperature; thus, hand calculations are a very tedious and time consuming operation.

A 5-point parabolic fit is a more accurate way of finding the derivative needed to calculate α^*. In this method an arbitrary parabola is fitted to the curve through five adjacent points and the derivative of the parabola is calculated at the mid-point. The accuracy [illegible] the rate of change of the slope of the curve and the increment between the five points chosen for curve fittings.

By either method, manual calculation of α^* requires a minimum of two to three hours per test, while a minimum time for an analog run is only 5 to 10 minutes including a proportionate share of the calibration time.

DIGITAL DATA REDUCTION

Digital data reduction is quite rapid, if the calculation time only is considered. However, transferring information to the computer from strip chart records can be quite tedious if done manually. If initial records from the alpha-rod test were recorded on tape, it would be more convenient to use a central digital computer. However, it is not always convenient or economical to use tape recorders for data recording and a visual record is not usually obtained. The initial purchase of analog equipment also provides some very flexible equipment that can easily be used for other data processing problems and experiment situations.

ANALOG DATA REDUCTION

GENERAL

The block diagram, Figure 2, represents the general idea behind the analog schematic, Appendix A, Figure A-1.

An F. L. Moseley Company optical curve follower is used to regenerate a signal proportional to the temperature on the original test record. The original test record may be run through the curve follower at speeds independent of the original recording speed thus providing for a large scope of test records that can be "handled" by the analog. The signal from the curve follower is split; one branch representing temperature going to the X-Y Recorder and the other branch continuing through the analog results finally in α^*. First T_o is subtracted out; then the signal is operated on by an F. L. Moseley logarithmic converter. The signal is then differentiated, resulting in a signal proportional to

$$\left(\frac{1}{T - T_o} \right) \frac{dT}{dt} = \frac{u^2}{\gamma^*}$$

The constant $1/u^2$ is "multiplied out" using a potentiometer. The final signal is proportional to $1/\gamma^*$, which when plotted on hyperbolic graph paper reads directly in γ^*. A photograph of the assembled system is shown in Figure 3. Further details of the equipment and its operation are given in the appendices.

ACCURACY OF RESULTS

Analog operation was checked by plotting known functions on strip char paper which were then used as an input to the analog. The known functions enabled a precise calculation of γ^* which could be compared with the analog results as a % error.

Another method of comparison was to use a parabolic fit to calculate the slope (and thus α^*) for an actual run and then compare this with analog results as a % difference.

Four comparisons are presented:

1. Figure 4 results from using a ramp function as an input.

2. Figure 5 is obtained from an exponential input.

3. Figure 6 is obtained from a parabolic input.

4. Figure 7 is obtained by using a temperature-time record.

Figure 4 is a hyperbola which the analog produces when a straight line, of slope equal to one, is plotted on strip chart paper and run through the curve follower. The calculated points agree quite well with the analog results; the error being about ± 3% for 13 points. This is good considering that a differentiator is in the analog circuit and that the output of the log converter is not matched to the input voltage range of the operational amplifiers. Looking carefully at Figure 4 (also Figs. 5 and 6) it is seen that the noise is symmetrical for these uniformly changing inputs.

Figure 5 shows the analog output when an exponential function, $T = 100e^{t/4.34^*}$, is used as an input. The result should be a constant, 0.230, starting at T = 100° and rising immediately to full value. The noise is greater for the lower values of T and damps out considerably at one-third full scale. These results are due to the rapidly changing log values for small changes in temperature at temperatures approaching T_o. The error is about ± 5% overall average (for 15 points) and about ± 4.4% over the last two-thirds of the curve (using 10 points).

---

* In the exponential equation used, 4.34 has the units of secs which makes the equation consistent. For this particular case 4.34 is equal to the factor α^*. In general, however, the form of any temperature-time record may be expressed as

$$T = T_o e^{tu^2/\alpha^*}$$

u^2/γ^* has the units of sec^{-1} and might be compared to a time constant for steady state conditions of heat transfer with constant thermal properties. More generally u and α^* may vary with the thermal conditions. We thus have a time constant for linear systems and a time variable for non-linear systems. The variation of u^2/α^* with temperature is easily produced by the analog.

Figure 6 shows the analog output for a parabolic input ($t^2 - 40\epsilon + 40T = 0$). The average error for 14 points is ± 3.5%. Seven additional points were calculated, but they are not shown on the graph due to crowding. However, the error is essentially the same when all the points are included.

Figure 7 shows analog reduction of the temperature record shown in Figure 1 compared with points hand calculated using the parabolic fit technique described earlier. More points were calculated but would not fit on the graph conveniently. The average error in Figure 7 is -7%. This 2 to 4% increase in the error is due to the irregular nature of the signal and to the steepness of the input curve. The negative error results from the phase lag of the output signal and a possible bias from an "offset calibration." With regularly increasing functions such as in Figures 4, 5 and 6, the phase lag error is at a minimum except for the very initial portion of the output (say 0.1 or less of the overall temperature range). Under ideal conditions, when the time constant of the overall analog is matched with the range and frequency of the input variation (see appendices) the error is symmetrical and includes only contributions from the various servo controlled devices or from the natural differentiator instability.

The limiting error of the system is about ± 3% while for actual temperature-time records the error will increase to an average of 5 to 10%. Since the temperature record is always rising the analog output will tend to lag causing an unsymmetrical error.

SUMMARY AND CONCLUSIONS

An analog data reduction system was developed for the NOL "Alpha" Rod Test for fast, accurate calculation of effective thermal diffusivity (γ^*). The difficulty of obtaining accurate slope measurements from irregular temperature curves was the major factor for seeking out an automated method for calculating γ^*. Analog data reduction was chosen for experimental convenience and flexibility of equipment.

The best accuracy of the data reduction system is ± 3%. More typically, when using irregular temperature records and including errors from routine calibrations, etc, the average error ranges from 5 to 10%. In addition, computation times were reduced to 5 - 10 minutes per test when they were formerly 2 - 3 hours per test.

Reduction of data from routine "alpha-rod" testing has given satisfactory results and the use of this type of equipment is recommended to others in similar situations.

APPENDIX A

NOTES ON SCHEMATIC

The schematic (Fig. B-1) is fairly simple and rather than explain operating principles in this report, the reader is referred to references (e) and (f).

Commercial equipment used in the system includes:

1. Beckman Quad Amplifier, Model 620-A (4-unit operational amplifier).

2. F. L. Moseley Logarithmic Converter, Model 60B.

3. F. L. Moseley X-Y-T Recorder, Model 135.

4. F. L. Moseley Model F-2 Optical Curve-Follower

5. Lambda regulated power supply, Model C-881M. Total cost of equipment, including strip chart recorder, about $10,000.

The inclusion of the log converter in the circuit satisfies two areas: (1) in the computation and (2) in reducing the rate of change of signal to the differentiator in the higher temperature regions of the input record. This allows an increase in the time constant of the differentiator and thus reduces the overall noise of the output. The initial portion of the output is noisier but an overall advantage is obtained.

No difference was noted in output noise level whether the system was operated with batteries or with a power supply; therefore, a regulated power supply was used for convenience.

The optical curve-follower must be kept operating smoothly, since any hold-ups in the optical head position are exaggerated in the output. The optical head requires the most attention in maintenance of components.

The log converter and X-Y Recorder both contain filters for 60-cycle noise, which would not be much of a problem except for saturating the differentiator. The smaller resistances and capacitors are used in the differentiator to prevent saturation or ringing. If the short in position number 4 (the upper left corner of the schematic) is inserted into the input of the differentiator, the output will gradually increase until the amplifier overloads (or is saturated).

Polystyrene capacitors were used to minimize leakage. Earlier, good quality paper capacitors were used, but the output of the differentiator was not symmetrical when two ramp functions were backed up on the input chart paper.

Codes for wiring the input, output plugs of commercial equipment are found in the respective operating manuals. Shielded wiring is used in all low signal areas and in all feedback loops in the individual amplifiers. The system was initially hooked up with commercial quick connecting plugs, which were unshielded, but the noise level was not significantly greater.

One improvement in the system would be to replace the present log converter with one with a higher output voltage range. The output of the present log converter is somewhat low for use as an input to an operational amplifier. Another improvement would be to add a 4 mfd capacitor to the differentiating circuit.

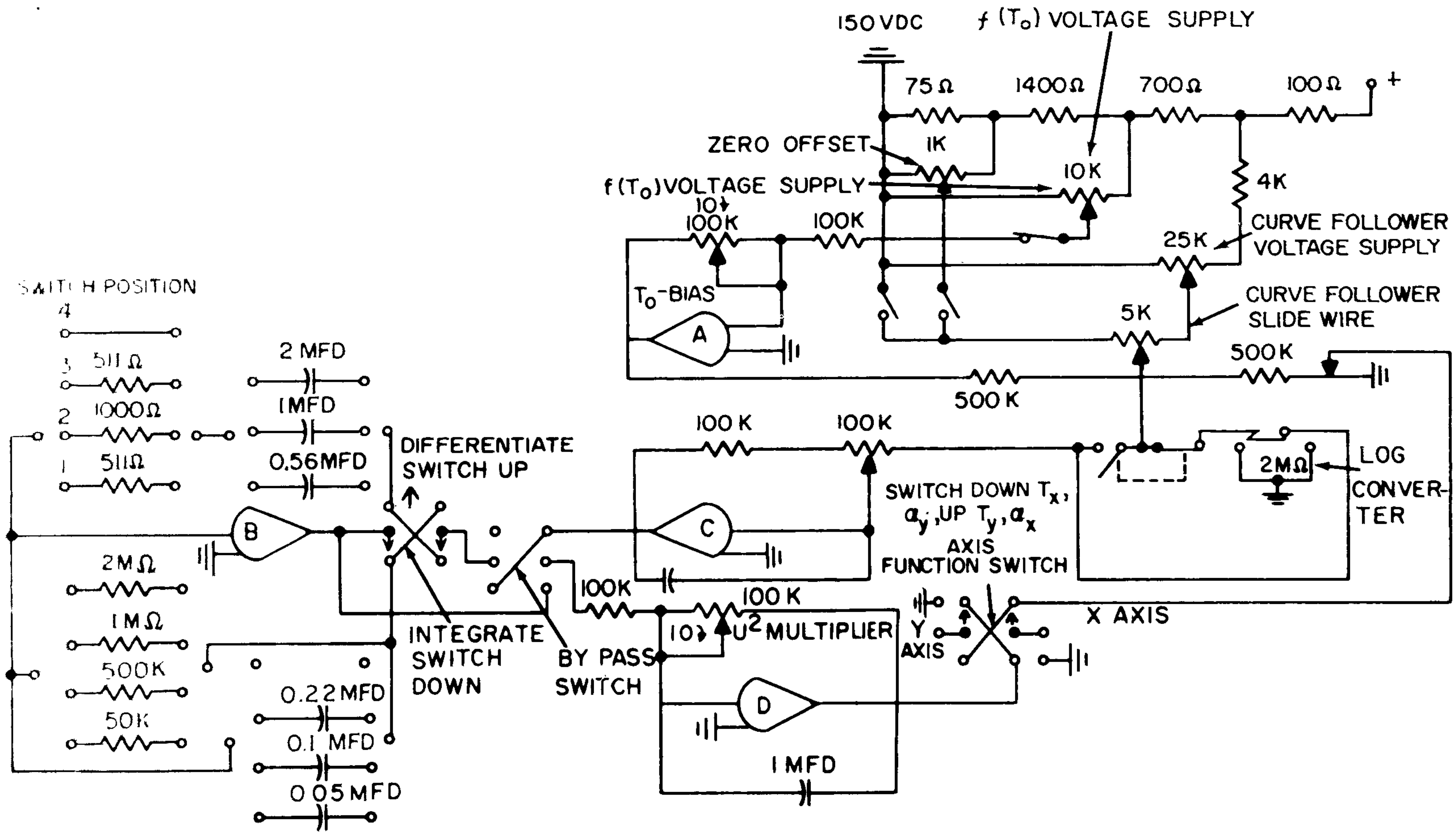


FIG. A-1 SCHEMATIC OF ANALOG DATA REDUCTION SYSTEM

APPENDIX B

EXPLANATION OF CONTROLS

The photograph of the control layout, Figure B-1, shows the relative position of the various switches, etc., as they appear. Referring to the photograph of the system, Figure 3; the area considered is labeled RC circuit switches, selection switches, and calibration potentiometers. A short written explanation of the use of each control is given. The number heading in the discussion corresponds to the position number of the control in the layout. The use of these controls in calibrating the system to calculate α^* is given in Appendix D.

1. The X-Y axis reversal switch provides some freedom in scaling when using the standard Cartesian coordinate system. On hyperbolic paper, α^* must be plotted on the customarily assigned X axis, while on rectangular coordinate paper α^* is usually assigned to the traditional Y axis: $T_X\alpha_Y$, switch up; $T_Y\alpha_X$, switch down.

2. The log by-pass switch is inserted to make the system more flexible for uses other than the calculation of α^*. It also provides a means of isolating the different components for checking individual operation (in conjunction with other by-pass switches). All by-pass switches have essentially the same function: switch up, log in.

3. The DI by-pass switch shorts out and isolates the differentiating-integrating circuits: switch up, DI in circuit.

4. The 4th switch selects the operation desired, differentiation or integration: switch up, differentiate switch down, integrate.

5. The T voltage supply regulates the voltage available to the linear branch of the circuit. It is not independent of the curve-follower voltage supply.

6. The log output multiplier is a "variable gain amplifier" used to multiply the output voltage of the log converter. This control is used in the maximum gain position when calculating α^*, since the maximum output of the log converter is only 120 mv in the 5 db/in. mode.

7. The curve-follower voltage supply regulator is what its name implies and is fed directly from the power supply through loading resistors to stabilize the power supply.

8. The T_O ten-turn potentiometer is an accurate linear potentiometer; it may be calibrated but it is often more convenient to subtract out T_O directly on the graph paper using this potentiometer in an arbitrary manner.

9. The T_o voltage supply may be used to either calibrate the T_o potentiometer or merely as an adjustment for the sensitivity of the T_o potentiometer. This control is not independent of curve-follower supply.

10. The $1/u^2$ multiplier is a ten-turn potentiometer for multiplying out u^2. Values must be less than 1 and there is a reciprocal relationship involved. It is always calibrated.

11. The curve-follower zero suppressor provides a floating bottom reference, when needed.

12. The DI capacitors are inserted in either the feedback loop or input of an operational amplifier. The 2 and 1 mfd positions are most commonly used.

Position 1. 2 mfd.

2. 1 mfd.

3. 0.56 mfd.

13. The filter capacitors are inserted in parallel with the DI resistors. They are for noise reduction when differentiating; they have no use when integrating and the blank position is selected.

Position 1. 0.22 mfd.

2. 0.1 mfd.

3. 0.047 mfd.

4. Open.

14. The DI resistors are in the feedback loop for differentiating or in the input of an operational amplifier for integrating. The 2 and 1 M positions are used most frequently.

Position 1. 2 MΩ

2. 1 MΩ

3. [illegible]00 K

4. [illegible] K

[illegible] when differentiating. [illegible]

Position 1. 5110 Ω

2. 1000 Ω

3. 511 Ω

4. Short.

16. The T_o by-pass switch isolates the precision negative voltage supply (see also item 2).

17. Zero suppressor by-pass switch - switch down by-passes the biasing system and grounds the negative end of the curve follower pot.

18. Pen lift - for X-Y recorder. Switch up; pen down.

19. Chart drive - on - off.

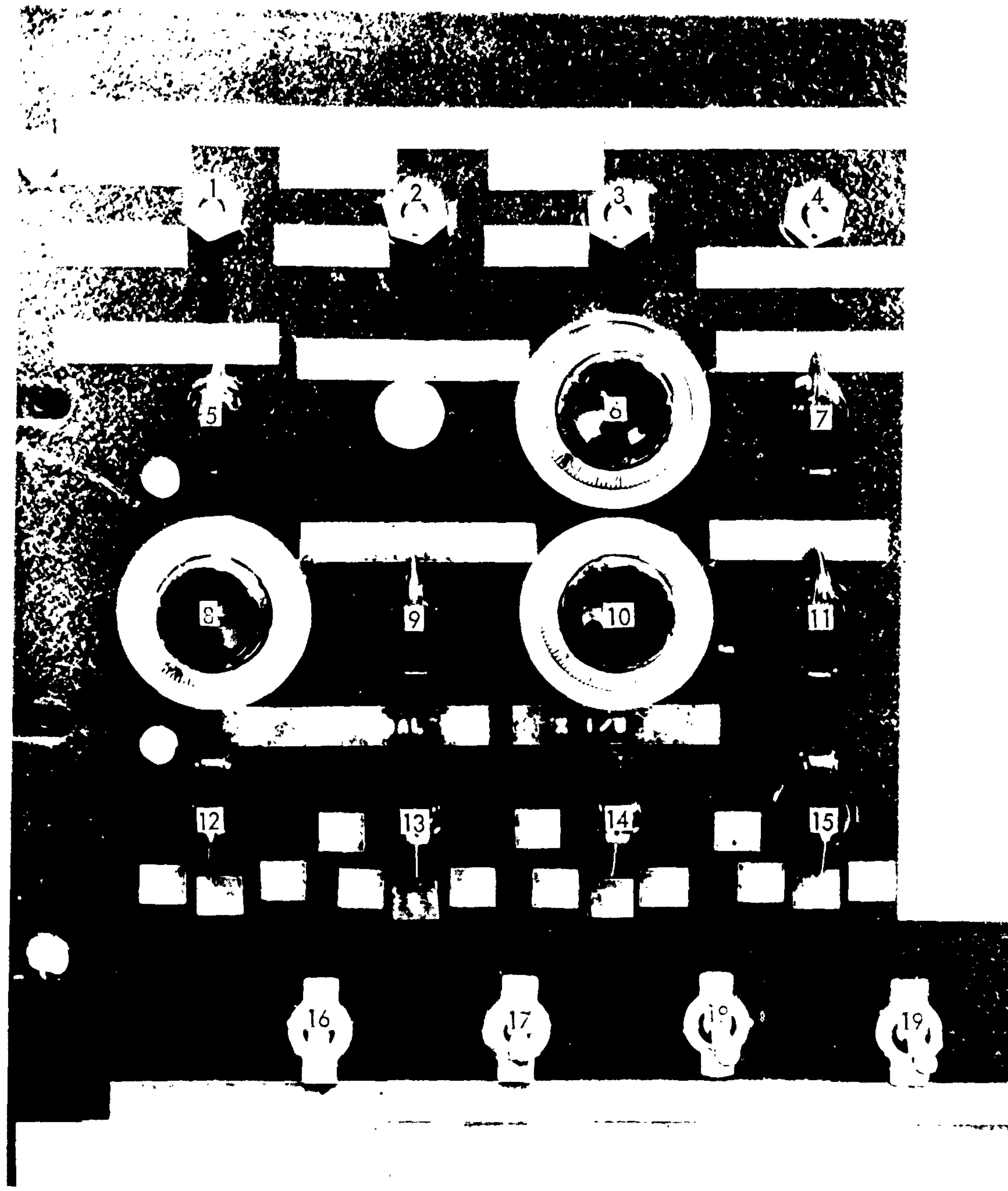


FIG.B-1 LAYOUT OF CONTROLS

APPENDIX C

OPERATION AND CALIBRATION

The function and location of each control not in a commercial instrument is covered in Appendix B. Before attempting to operate the system, one should become familiar with the controls on each instrument and the location of the controls.

CALIBRATION PROCEDURE

1. Turn all instrument power switches on:

   a. X-Y Recorder

   b. Power supply

   c. Logarithmic converter

   d. Operational amplifier unit

   e. Curve-follower

2. Allow fifteen minutes for warm up.

3. Balance outputs on Beckman, 4-unit, operational amplifier (see instrument instruction manual if you are not familiar with this type of instrument).

   a. Place amplifier channel switches in "bal" position.

   b. Place the amplifier panel meter switch in "bal" position.

   c. Adjust potentiometer extensions until panel meter balances about zero; there will be a small deflection about zero.

   d. Return amplifier channel switches to ∞ (infinite) position.

   e. Return panel meter switch to 150 position.

4. Place log converter output range switch on 5 DB/in.

5. Place log converter input attenuator on 0 DB.

6. Place log converter current mode-selector on DC.

7. Set log booster potentiometer on max (10).

8. Set T_o potentiometer on low number between 1 and 3.

9. Set u^2 multiplier pot. on 5.

10. Set main power supply or curve-follower voltage supply pot. (on) 1/2 position, approximately (180° rotation).

11. Set T_o supply to approximately 90° rotation.

12. Set T supply to approximately 110° rotation.

13. Set zero suppressor to 0° rotation.

14. Set differentiator resistor filter to 2nd or 3rd position (not in any case 1st position).

15. Set differentiator feedback resistor selector to 1st position.

16. Set differentiator input capacitor selector switch to 1st position.

17. Set differentiator filter capacitor on 2nd or 3rd position.

18. Set differentiator by-pass switch on by-pass.

19. Set log converter by-pass switch on in position.

20. Set DI switch on differentiate.

21. Set axis reversal switch on $\alpha_y T_x$.

22. Set T_o by-pass switch on in position.

23. Set zero suppressor by-pass switch on in position.

24. Turn off error alarm on curve-follower (if on).

25. Push reset button on curve-follower, if the optical head is not tracking.

26. Check balance on curve-follower (see instruction manual on this instrument if you are not familiar with its operation).

26a. Place opaque white paper on curve-follower table.

26b. Adjust balance until there is no drift of head position over the entire range of operation of the head.

27. Wipe all carriage bearing guides (or runners) to clean off gum and/or dirt. Clean with alcohol and a lintless tissue and resurface with a lintless tissue moistened with fine light oil.

28. Rebalance operational amplifiers (step 3).

29. Draw 10 horizonatal lines about two inches long, one on each major unit of the scale on the strip chart paper in the curve-follower drive. Use ordinary pencil lead (not hard) or india ink.

30. Draw a line on the strip chart through the units 1,1, 2,2, 3,3 etc. This is approximately a 45° line. (The horizontal or time units are one inch; the vertical or temperature units are less than one inch.) Place a short lead in line at the zero position about two inches long (you can use the first line in step 29).

31. Important - always use L and N No. 742 paper or F. L. Moseley chart paper in the curve-follower. Other equivalent paper sizes usually will not do because the grid lines interfere with the tracking operation of the curve follower.

32. Adjust the gain on the optical curve-follower until the photo-electric head just breaks into oscillation when positioned over a line, then back off the gain to obtain stability.

33. Place the optical head over the full-scale line (drawn in step 29).

34. Interchange the leads to the X-Y Recorder. By-passing an operational amplifier or the log converter causes a change in sign of the voltage. The voltage proportional to temperature(on the X axis) will not invert since no operations using amplifiers are performed in this branch of the circuits.

35. Place a piece of cartesian coordinate graph paper square in the X-Y Recorder. Use the pen carriage to trace out the base lines as an alignment check; use the X-Y Recorder zero suppressor controls to move the pen.

36. Adjust the y axis voltage calibration on the X-Y Recorder for full-scale deflection on graph paper - use recorder pen. If the full-scale deflection of the original thermocouple record is, for example, 50 mv, look up the corresponding temperature, °C, for a chromel-alumel thermocouple and take the log. (The y axis is then calibrated in proportion to the log.)

37. Adjust the zero value by turning the zero suppressor until the pen is over the zero base line when the log converter meter is at zero. Zero or -60 DB is obtained on the log converter by adjusting the T_0 pot.

38. By moving the optical head over the column of lines, the full range of the log converter may be scanned. Adjust the curve-follower voltage supply and the Y axis voltage calibrator and the T_0 control until a satisfactory log scale is obtained on the Y axis of the X-Y plotter.

39. Calibrate the X axis by manipulating the T voltage supply and the X axis voltage calibrator until a scale is obtained on the X axis of the plotter that corresponds to the Y axis log scale.

40. The X-Y axis switch should now be placed in the $\alpha_X T_Y$ position.

41. Switch the DI by-pass switch to <u>in</u>. (Invert leads as necessary.)

42. Place the optical head over the zero position horizontal line (as drawn in steps 29 and 30).

43. Plot unit values of α^* on hyperbolic graph paper. Use values from the calibration table at the end of this section for most common calibrations.

44. Place a sheet of hyperbolic coordinate graph paper in the X-Y plotter. The rest point of the X axis will be on the right and the zero temperature line on the bottom of the graph.

45. Readjust the temperature scale, now on the Y axis, by scanning the optical head over the penciled unit lines on the strip chart and manipulating the T voltage supply and the Y axis voltage calibrator on the X-Y Recorder.

46. Set the chart drive gear to 16"/min.

47. Place the optical head over the zero base lead in line to the 45° line.

48. Adjust the T_o control until the log converter reads 60 DB and the X-Y Recorder (pen) is at the desired zero position.

49. Turn on the chart drive.

50. Adjust the X axis voltage calibrator until the traced out hyperbola of the X-Y Recorder corresponds to the plotted points as calculated for a straight line input.

The system is now calibrated for calculating α^* on reciprocal graph paper.

<u>OPERATING PROCEDURE</u>

Temperature records are run through in the same manner as the 45° line for calibration. Remember to set the u^2 multiplier as explained on page C-5. The zero line is taken as the initial temperature on the temperature record. Adjust the T_o control until the logarithmic converter meter reads -[illegible] DB. Coordinate the y axis pen position with the zero base line on the strip chart before subtracting out T_o.

MULTIPLYING OUT u^2

The u^2 multiplier potentiometer has a unit range from one to ten and it is the feedback loop of an operational amplifier. By assigning a value of one to the mid-position, you can multiply by a constant greater or less than one.

The electrical output of the system, with the u^2 pot. at 5.00, is proportional to $\frac{u^2}{\alpha}$; however, the hyperbolic coordinate graph paper inverts this factor and the system is calibrated to read α/u^2. Multiplying by a constant proportional to $1/u^2$ will result in a signal $1/\alpha$, which can be read on an inverted scale as α.

The ablation rate should be expressed in cm/sec x 10^{-2}. The decimal does not always follow the first unit, as in scientific notation, e.g., 28.9 x 10^{-2}, 0.289 x 10^{-2} and 2.89 x 10^{-2}. The ablation rates encountered in the current test facilities will usually be in the range of one or two units x 10^{-2}. Squaring gives xx.x (10^{-4}), which is a convenient range to use as a plotting scale factor, i.e., α x 10^{-4}. Try to plot the final results on the hyperbolic paper in roughly the same range as the original calibration. For example:

$$u = 7.04 \times 10^{-2}, \; u^2 = 49.5 \times 10^{-4}$$

On an input curve with a constant slope of 100°/sec (such as the 45° calibration line), the first unit value of α would be 1 x 49.5 x 10^{-4}. A scale factor must be applied to bring this number in the range of 0.7 to 1.4 to obtain a readable graph. If the calibration speed is different than the run speed, the scale factor must be adjusted.

The u^2 pot. dial is used as follows:

Unit	1	2	3	4	5	6	7	8	9	10
Correlating Graph Value	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50
Reciprocal Factor	1.67	1.43	1.25	1.11	1.00	0.910	0.843	0.770	0.715	0.667
Dial Setting	0.835	0.715	0.625	0.555	0.500	0.455	0.416	0.385	0.357	0.333

By the table using the example $u^2 = 49.5 \times 10^{-4}$, 1/scale factor = 1/50, $u^2 = \frac{49.5}{50} = .991$. u^2 dial setting $= \frac{1}{.991} \times \frac{1}{2} = .505$. The $\frac{1}{2}$ factor is used to compress the scale on the dial. When one would read the resultant graph, the point would be 0.991 x 50 = 49.5 x 10^{-4} at 100.

CALIBRATION TABLE

Table C-1 gives α^* values, etc., for the most common calibration of the system. This depends on the initial full-scale temperature selection during testing, or it may be arbitrary if it is desired to select only a portion of the test record for data reduction.

Notice that decreasing the original recording speed by a factor of four decreases the slope by a factor of four and thus increases all α^* values by a factor of four.

Looking at the 60"/min recording speed, all calibrations have the same α^* value at say unit two, but the second unit line represents a different temperature in each case. These calculations were made assuming $u^2 = 1$ and $T_0 = 0$, resulting in $\alpha^* = \frac{T}{\frac{dT}{dt}}$ if the slope is constant as in the 45° calibrating line at x°/sec, then $\alpha = 1, 2, 3, 4, 5$, etc.

Some notes for operating:

a. Increasing the chart drive speed by a factor of two increases the output of the system by a factor of two, but on the hyperbolic paper this decreases the absolute value by a factor of two. The original scale factor must then be multiplied by a factor of two. This is merely inverse for decreasing chart speeds.

b. Decreasing the product of the R and C values selected by a factor of two decreases the output by a factor of two and has a similar effect as decreasing the chart speed.

c. Small RC products result in greater noise but better accuracy (except when the noise becomes so large that the results are difficult to interpret).

d. The system does not have to be calibrated when changing chart speeds but does when changing RC values, especially when changing capacitors, since they are not precise values of C.

e. Recalibration of the system requires only the steps from No. 43 of the procedure using a piece of graph paper with known values of α^* plotted. The log converter is fairly stable and the whole system will hold a reasonable calibration for several days, although this should be checked at least at the beginning of each day.

f. The amplifier units should be balanced from time to time. The balance will change somewhat if the amplifier unit is not allowed to warm up properly.

g. The curve-follower operation must be kept as smooth as possible. Keep the head carriage bearings clean and well adjusted and keep the carriage bearing guides clean and lightly oiled.

h. The optical head must be kept well adjusted. This requires using an oscilloscope monitor and the procedure outlined in the instruction manual. The head should move with evenly equal traking force over the complete span when the servo control is working at operating conditions. Uneven operation of the head over the span requires readjustment. Loss of head control signal or decreases in the control signal also requires attention. The optical head should not be removed or tinkered with by the operator unless he is thoroughly familiar with its operation, since readjustment is tedious.

TABLE C-1

CALIBRATION TABLE

L and N 742 1/ Unit	1000°C Calib. 100 X 15	Common Log	50 mv Calib. °C Equi.	Common Log	55.81 mv Calib. °C Equi.	Common Log	Recorder Chart Speed 60"/min. α^*	$1/\alpha^*$	15"/min α^*	$1/\alpha^*$
1	100	2.000	124	2.093	137	2.137	1	1.00	4	0.25
2	200	2.301	247	2.393	274	2.438	2	0.500	8	0.125
3	300	2.477	370	2.568	411	2.614	3	0.333	12	0.0825
4	400	2.602	494	2.694	548	2.739	4	0.250	16	0.0625
5	500	2.699	618	2.791	685	2.836	5	0.200	20	0.0500
6	600	2.778	741	2.870	822	2.915	6	0.167	24	0.0418
7	700	2.845	864	2.937	959	2.981	7	0.143	28	0.0358
8	800	2.903	988	2.995	1096	3.040	8	0.125	32	0.0313
9	900	2.954	1112	3.046	1233	3.091	9	0.110	36	0.0278
10	1000	3.000	1235	3.092	1370	3.137	10	0.100	40	0.0250

1/ L and N refers to the unit lines broken down into 10 major subdivisions on L and N Number 742 strip chart paper.

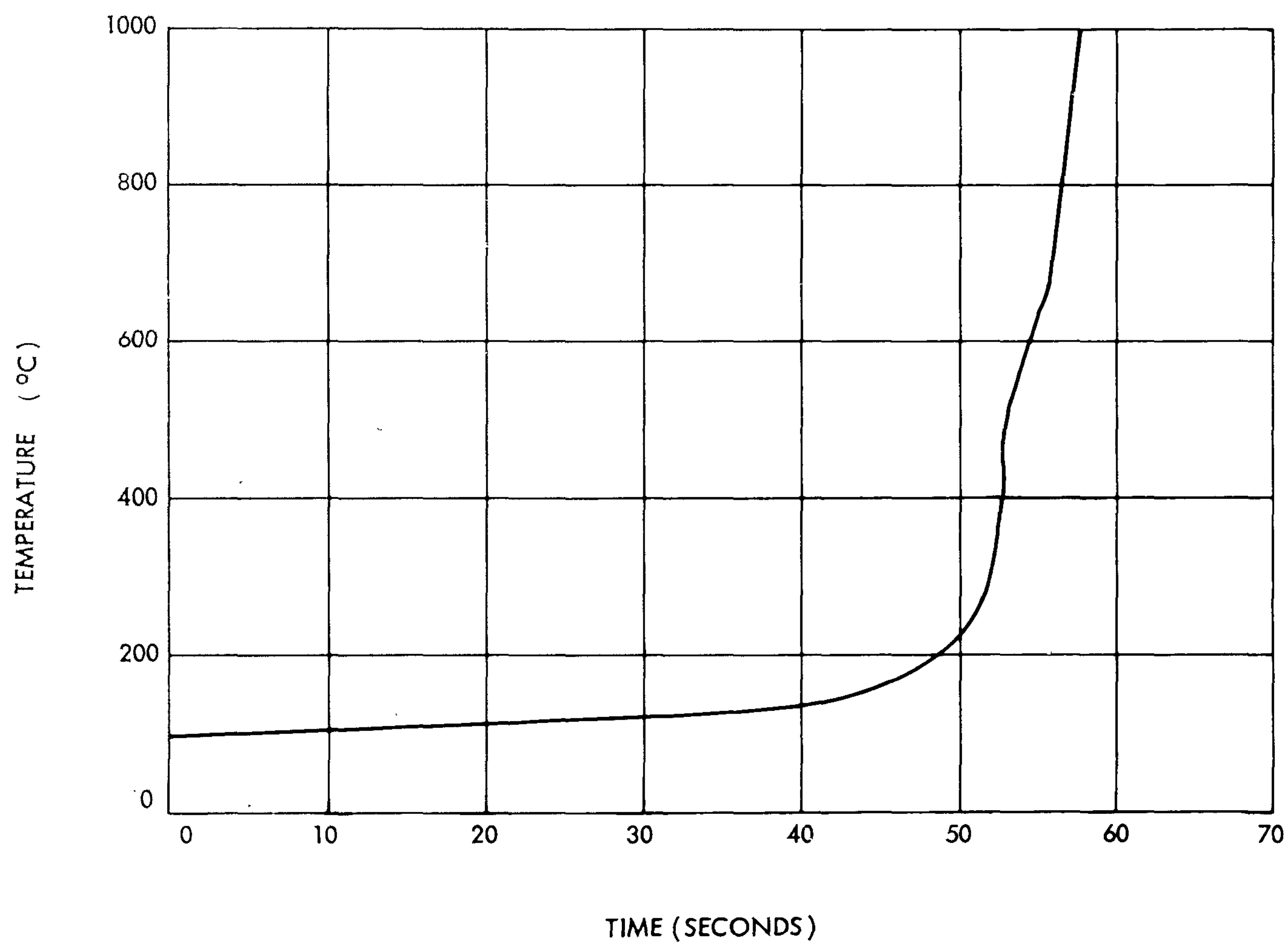
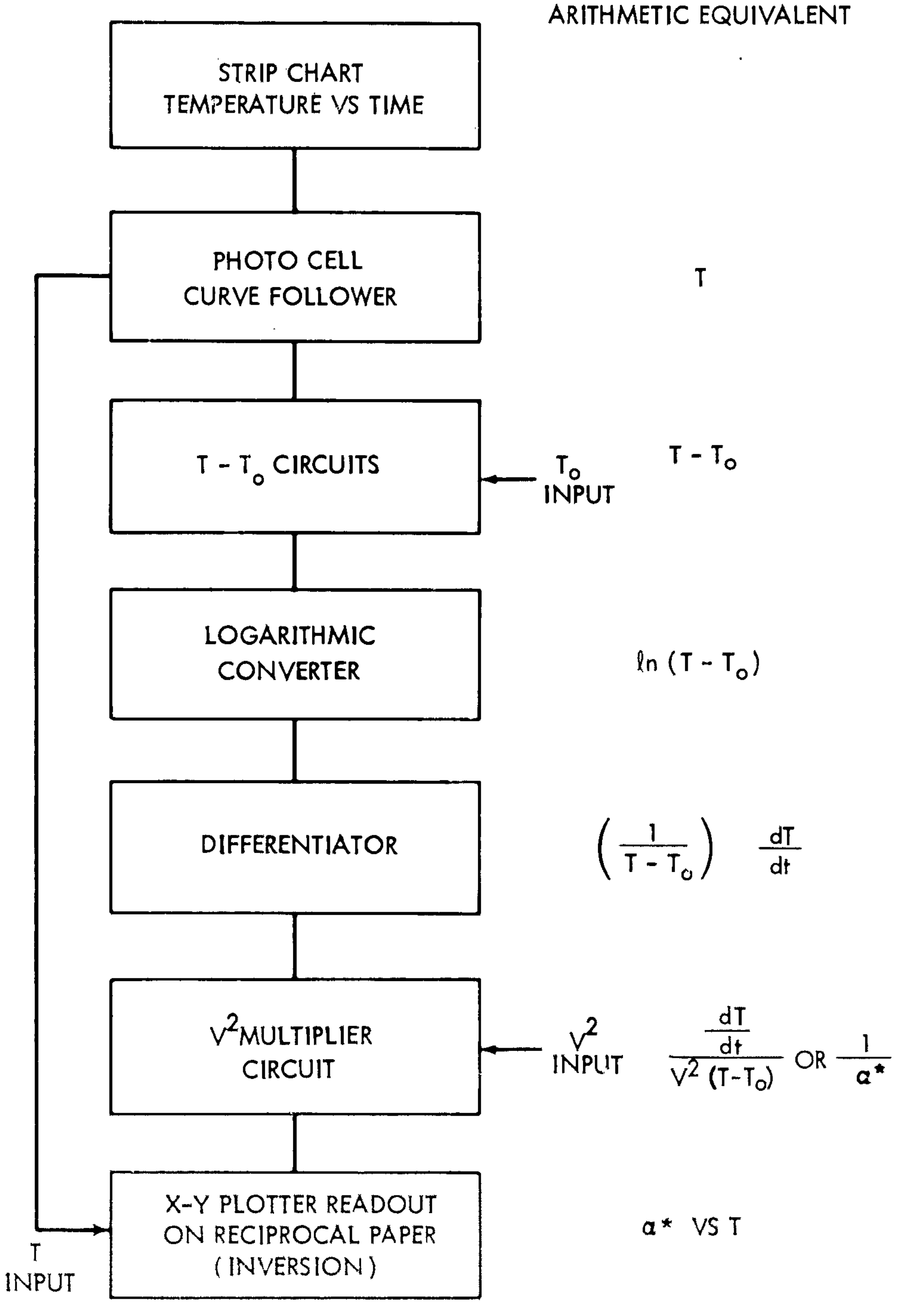


FIG. 1 TEMPERATURE-TIME RECORD FOR A TYPICAL NOL α -ROD TEST IN AN OXY-ACETYLENE TORCH (MATERIAL; EPON - 1031 - REFRASIL CLOTH LAMINATE)



T = TEMPERATURE AT TIME t
T_o = AMBIENT TEMPERATURE
V = SPECIMEN FEED RATE
α^* = EFFECTIVE THERMAL DIFFUSIVITY

FIG. 2 BLOCK DIAGRAM OF DATA REDUCTION SYSTEM

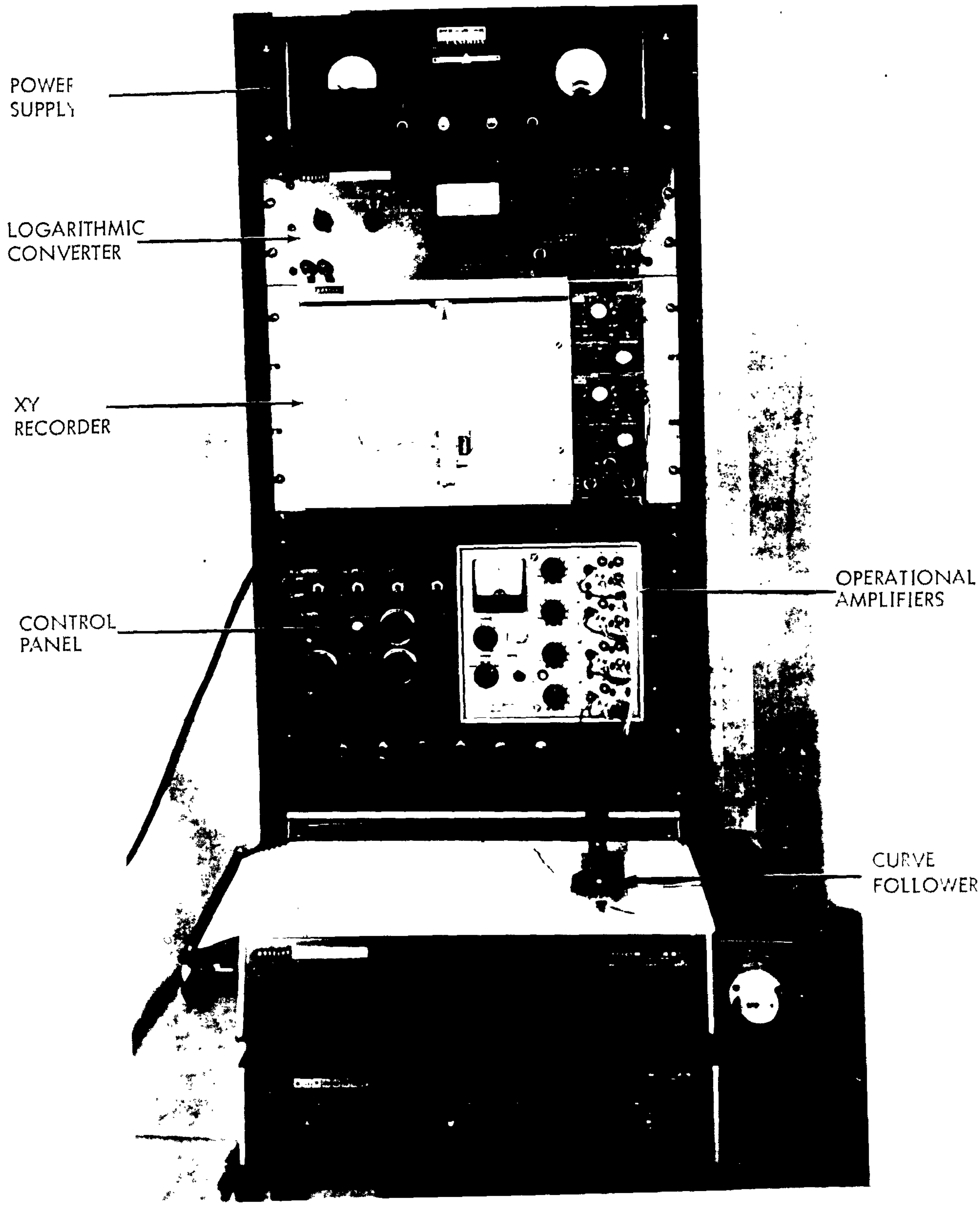


FIG.3 PHOTOGRAPH OF ASSEMBLED ANALOG

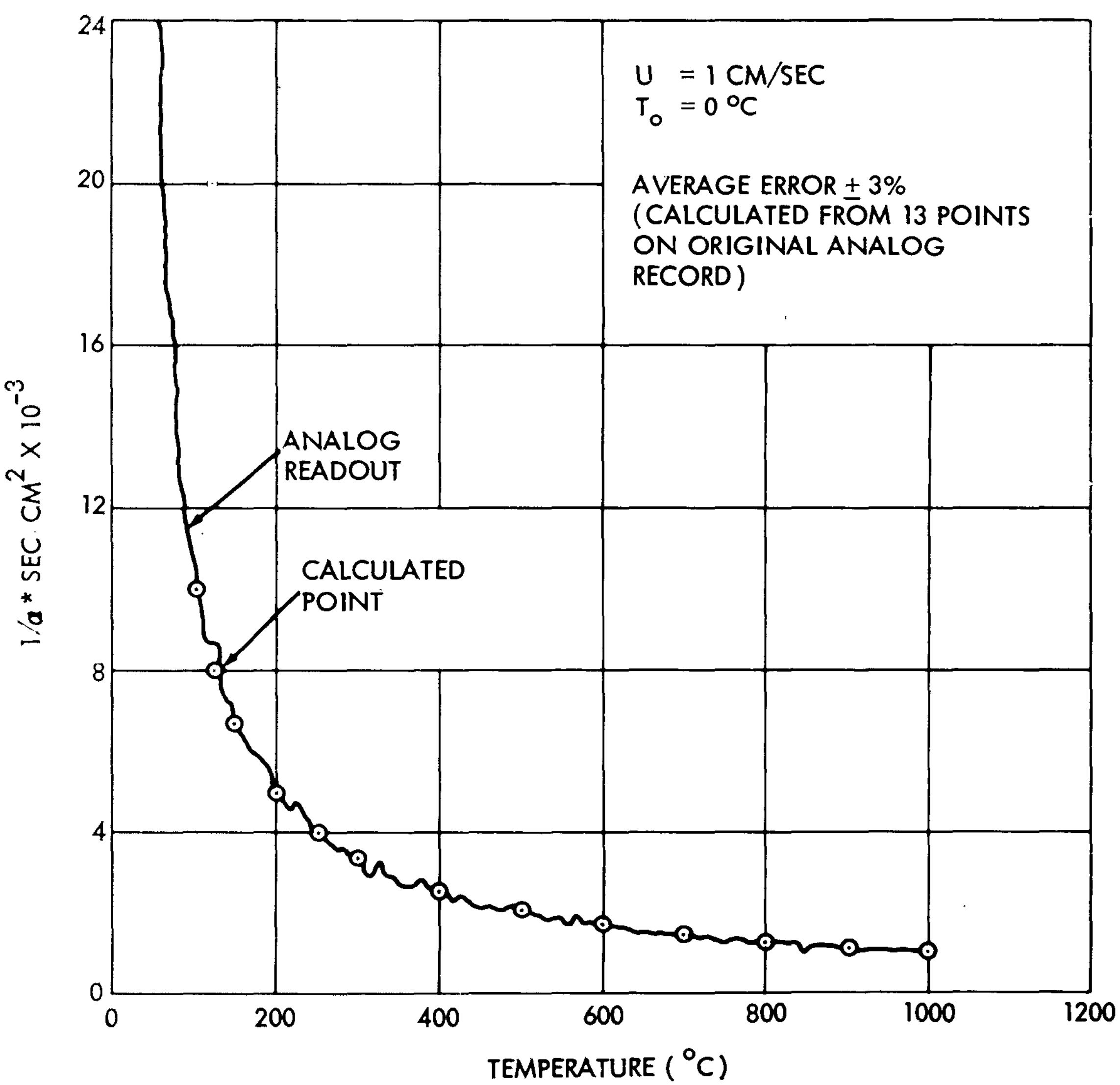


FIG. 4 COMPARISON OF ANALOG DATA REDUCTION OF t = T WITH CALCULATED VALUES OF THE EFFECTIVE THERMAL DIFFUSIVITY (a*)

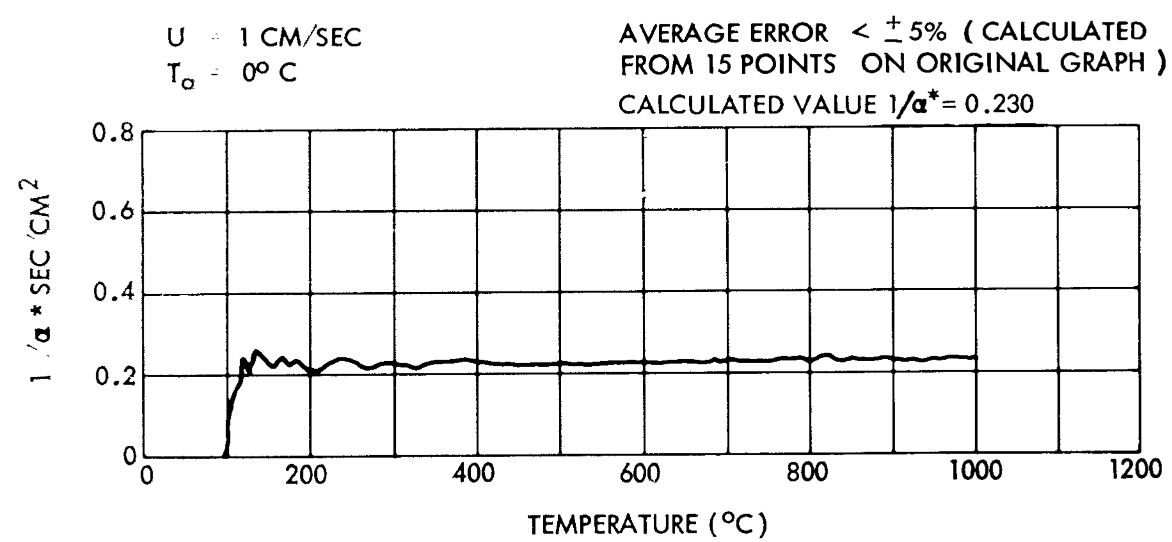


FIG.5 COMPARISON OF ANALOG DATA REDUCTION OF $T=100\,e^{t/4.34}$ WITH CALCULATED VALUES OF THERMAL DIFFUSIVITY (a^*)

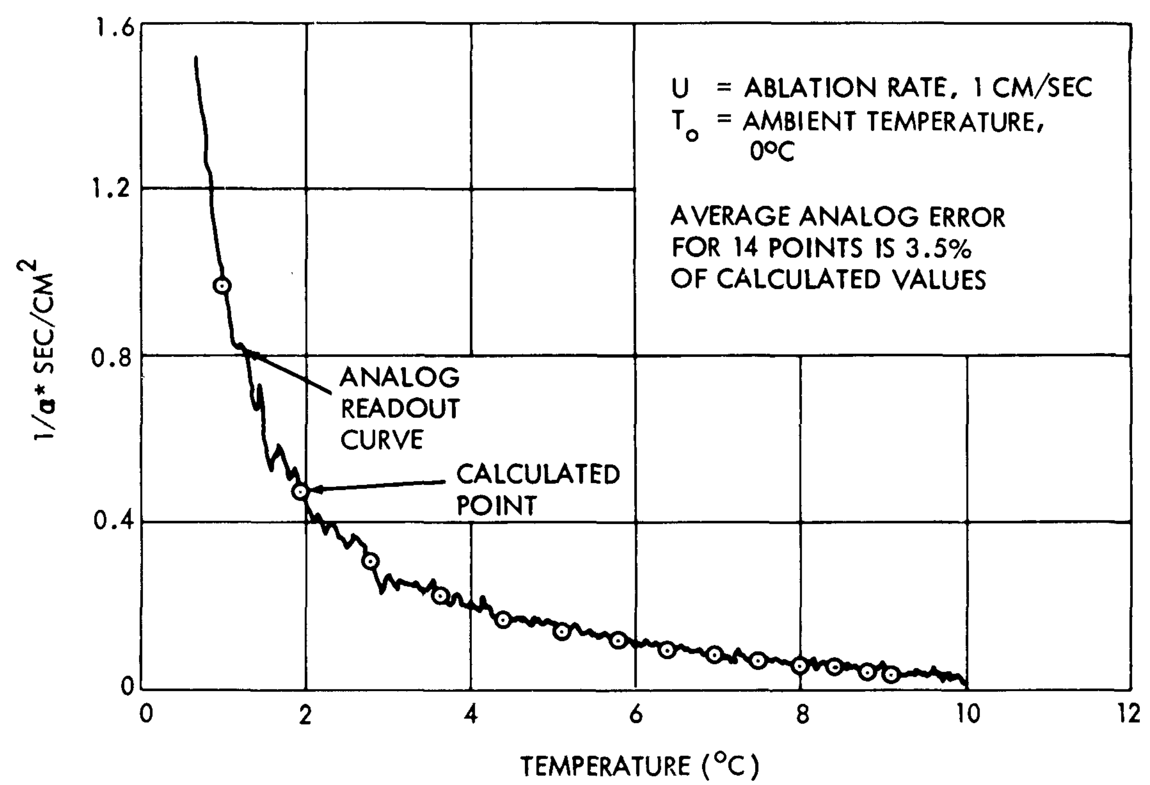


FIG. 6 COMPARISON OF ANALOG DATA REDUCTION OF $t^2 - 40t + 40T = 0$ WITH CALCULATED VALUES OF THERMAL DIFFUSIVITY (α*)

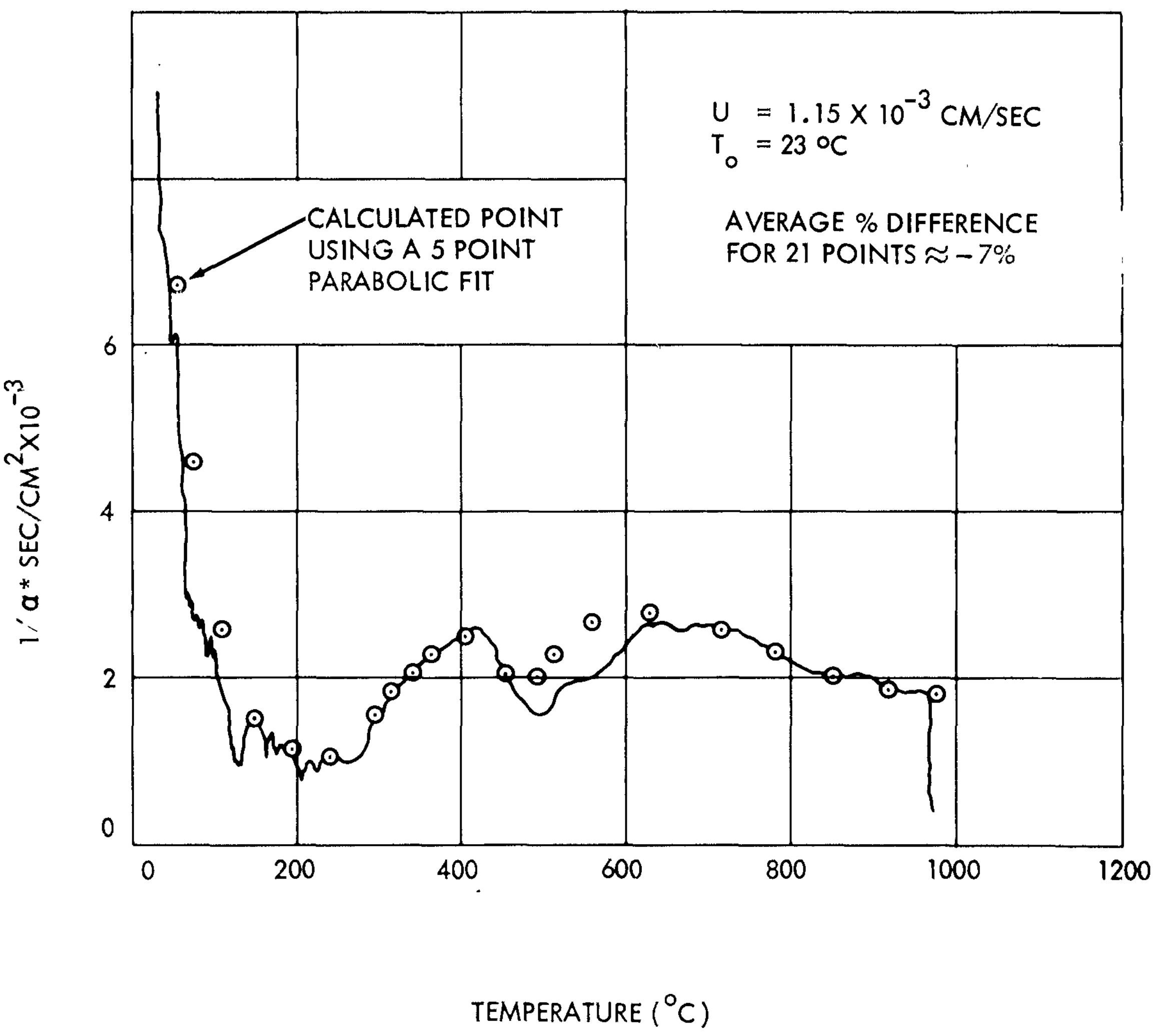


FIG. 7 COMPARISON OF ANALOG DATA REDUCTION OF FIG. 1, A TYPICAL TEMPERATURE-TIME RECORD, WITH CALCULATED VALUES OF EFFECTIVE THERMAL DIFFUSIVITY α *

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5 AUTHOR(S) (Last name, first name, initial)

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